

Theoretical and experimental investigations of a downdraft biomass gasifier-spark ignition engine power system

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ABSTRACT

A mathematical model which was developed to predict steady state performance of a biomass downdraft gasifier/spark ignition engine power system is described. A mathematical model of the integrated system consists of two parts: the fixed bed downdraft gasifier and spark ignition internal combustion engine models. For calculations the gasifier is split into three zones, namely drying – pyrolysis, oxidation and reduction sections. The gasifier's mathematical model consists of three separate sub-models, each describing the processes in the corresponding zone. The process taking place in the reduction zone has been described using chemical kinetic principles in order to avoid introduction of assumptions related to achievement of the thermo-chemical equilibrium state during gasifier's operation. The model is capable to accurately predict molar concentrations of different species in syngas (CO_2 , CO , H_2O , H_2 , CH_4 and N_2) and the temperature profile in the gasifier along its height. This information then can be used for sizing the reactor and material selection. The engine's model is based on the fuel–air thermodynamic cycle for spark ignition engines and such model takes into account the composition of syngas used as fuel. The engine's model also takes into account effects of heat losses in the cycle through the walls of the cylinders and due to the gas blow by. Finally, the influence of dissociation processes during the combustion and the residual gases remaining in the cylinders at the beginning of the compression stroke is accounted for computations of the engine's performance. The numerical results obtained using the proposed model are in a good agreement with data produced with the use of other theoretical models and experimental data published in open literature and with experimental data obtained in these investigations. The proposed model is applicable for modelling integrated downdraft gasifier/engine biomass energy systems and can be used for more accurate adjustment of design parameters of the gasifier and the engine in order to provide the higher overall efficiency of the system.

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1. Introduction

Gasification is one of the main biomass conversion technologies with internal combustion engines being frequently used as prime movers in biogas power generation units. In biomass gasifiers a limited amount of oxygen/air is supplied to biomass placed in a reactor in such a way that the fuel/air ratio is below the stoichiometric one. This results in burning of a relatively small part of biomass which generates heat to maintain a series of thermo-chemical processes with a mixture of gases being generated as a final product (called syngas or producer gas). During gasification four key processes occur inside the reactor, namely drying, pyrolysis, oxidation and reduction, and each of these processes has

certain physical and chemical features. In downdraft gasifiers, unlike other types of reactors, it was observed that the above processes are divided in space, i.e. these reactions take place in different zones of the reactor. A number of authors, namely Giltrap et al. [1]; Jayah et al. [2]; Gao and Li [3]; Sharma [4] and Ratnadhariya and Channiwalla [5], agree that, when considering downdraft gasifiers, the modeling of chemical reactions taking place in different zones should be carried out separately.

As a result of theoretical and experimental investigations conducted at the Center for Excellence in Distributed Generation (NEST) at the Federal University of Itajuba (Brazil) and in the School of Computing, Engineering and Information Sciences of Northumbria University a simple three-zone model of a fixed bed downdraft gasifier with a single-stage air supply was developed to describe processes of drying, pyrolysis, oxidation and reduction for rapid estimation of the syngas composition and such the model is a further modification and development of mathematical models

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previously published in open literature. To describe the overall operation of the biomass power generation system a mathematical model of a spark ignition internal combustion engine is used which is based on the fuel–air thermodynamic cycle. Such the cycle takes into account the composition of syngas as fuel, heat losses in the cycle due to heat transfer to the walls of the engine cylinders, the dissociation processes which occur during combustion of fuel and the blow by (the leakage of gases between piston sealing rings and the cylinder wall). Additionally, the engine's model accounts for the influence of residual gases in the cylinder at the beginning of the compression stroke and for variations in thermo-physical properties of the fuel–air and residual gases mixture and of combustion products.

2. Experimental setup

Fig. 1 presents an appearance of a 30–50 kW_{th} fixed bed downdraft gasifier built by Thermoequip for tests at NEST of the Federal University of Itajuba. The gasifier is for the production of syngas from wood blocks and is coupled to an internal combustion engine. When used with internal combustion engines gas produced (further referred to as producer gas or syngas) should satisfy the engine's manufacturer fuel quality requirements regarding the tar and particulate matter concentration which should be less than 35 mg/Nm³ at the gasifier's exit and less than 10 mg/Nm³ at the fabric filter outlet, respectively. The gasifier's design specification is presented in Table 1. The gasifier is made of carbon steel with an internal refractory layer. Its total height considering the biomass feeding hopper and the ash discharge system is about 2.2 m. The internal and outer diameters of the casing are 300 and 500 mm, respectively. Several K-type thermocouples are installed inside the reactor along the gasifier's height to measure temperature levels in its different sections. Information on the thermal state inside the reactor is required to maintain optimal operational conditions to efficiently carry out thermo-chemical processes of biomass



Fig. 1. An appearance of the fixed bed downdraft gasifier tested at the Federal University of Itajuba.

Table 1
Design specification of the gasifier.

Thermal power	Up to 50 kW
Expected engine electrical power	Up to 10 kW
Specific thermal power	1200 ± 500 kW/m ²
Biomass mass consumption rate (15% moisture content wet basis)	12 kg/h
Biomass particles size	2–6 cm
Air factor	0,35

conversion by controlling and adjusting the air flow supplied to the reactor. The reactor is made of vertical sections and, in general, can be used as either single- or double-stage air-supply reactor with separate air-inlets to each section.

To avoid channeling and bridging within the volume of biomass inside the reactor, a vibrating mechanism driven by an electrical motor with a special timing device is installed and this mechanism generates vibration motions inside biomass at regular time intervals. Such vibrations maintain continuous downwards movement of biomass in the reactor. Another similar vibrating mechanism is installed in the lower part of the gasifier to provide grate shaking which results in the ash discharge. Fig. 2 presents the system's schematic including an auxiliary equipment.

If the gasifier works with a single stage of the air supply then the controlled amount of air is provided to its middle section. When used as a double-stage gasifier, the air supply to the reactor's first stage provides conditions for biomass partial combustion with

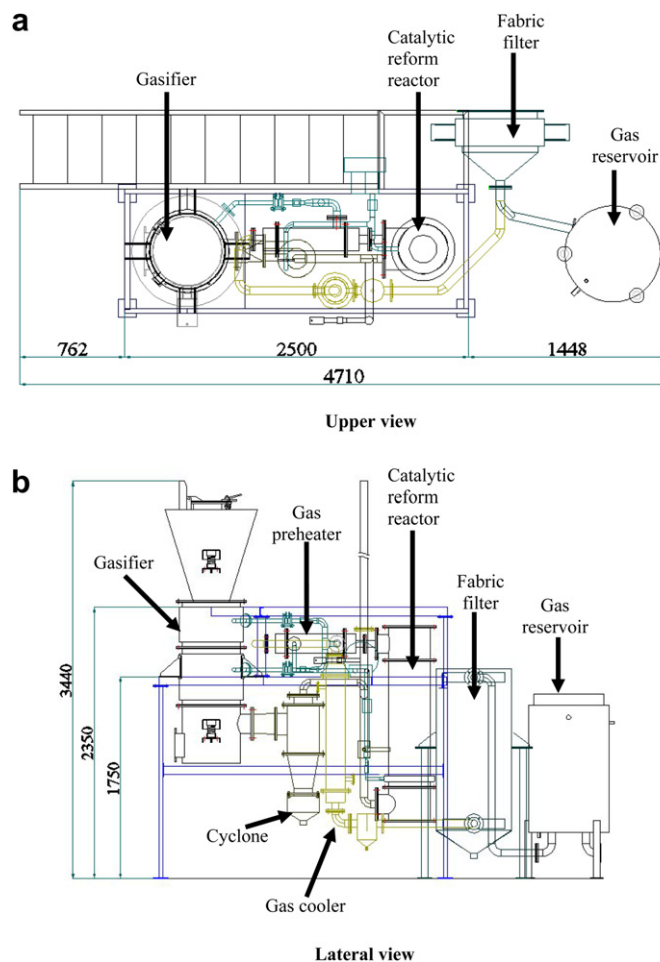


Fig. 2. Schematic diagram of the downdraft gasifier.

a heat release maintaining the drying and pyrolysis phases. The drying section is located in the gasifier's top part, where the distillation process of the lighter compounds of biomass takes place. In the pyrolysis zone, which is located just below the drying zone, the volatilization of the biomass organic compounds occurs and char is produced. This char is gasified later in the process. The main goal for using the second stage of the air supply to the oxidation zone is efficient conversion of tar into syngas to such a level which satisfies requirements for its application in ICEs. Additionally, the second stage air supply also contributes to the oxidation and reduction processes taking place in the reactor.

Syngas leaves the reactor through the exit in its lower part passing through a layer of glowing char and ashes and this provides an additional cleaning effect. As mentioned above, the grate supporting the bed is vibrated at regular time intervals for discharging ashes. The particulate matter in syngas is removed in two phases: first syngas flows through a cyclone separator, which has an internal insulation layer to maintain the high temperature of syngas which is necessary for the efficient operation of the catalytic reformer reactor – CRR. In this reactor tar, which was not thermally cracked in the gasifier, is catalytically converted into hydrogen and methane. The CCR is made of nickel wire coils placed in the thermally insulated cylindrical steel casing and operates at the 800–900 °C temperature range. After passing the CCR syngas is cooled down and then is directed to the fabric filter in which the further particulate matter removal process takes place. Finally, the cleaned and cooled down syngas is accumulated in the special reservoir which stabilizes its flow rate to the engine. The heat released during the cooling process of syngas is used to pre-heat air supplied to the gasifier in a specially made air pre-heater.

The gasifier is coupled to the modified two-cylinder Yanmar diesel engine which is shown in Fig. 3. The engine alterations include installation of spark plugs in the head of cylinders (one per cylinder) and application of a set of double regulating valves in the engine's syngas and air induction system. The double valve system provides a finer adjustment of syngas and air mass flow rates. The engine has the cylinder bore and piston stroke equal to 90 mm with the compression ratio being 12. The ignition timing in the cylinders can be regulated.

During experimental investigations the reactor was filled with eucalyptus wood blocks and the gasifier operated in a single-stage air-supply regime. Air was supplied to the oxidation zone of the gasifier. The spark ignition engine was fuelled by syngas produced in the gasifier and tested under variable load–constant speed

conditions. In the tests the mass flow rates of syngas and air were gradually increased and the engine's speed was maintained at 1800 rpm by increasing the engine's load. The electrical power produced by the engine's generator varied from 1.45 to about 5 kW_e. The original engine built for operation with LPG produces up to 10 kW_e and therefore the engine's power de-rating when fuelled with syngas is about 50%.

3. Calculation scheme of the gasifier

Fig. 4 shows the calculation scheme of the downdraft gasifier with three separate zones used in the mathematical modeling process. The downdraft gasifier is a fixed bed reactor, in which biomass is fed from the top whilst air is supplied to the reactor in its middle section and syngas comes out the exit at the bottom of the reactor.

Drying and pyrolysis processes take place at the top section. With the increase in the biomass temperature moisture is released and thermal decomposition of biomass takes place resulting in production of char, water vapour and a number of volatile species such as CO, CO₂, H₂, CH₄ and C₂H₂. The sub-model for description of these processes in the gasifier's top section is based on the model of the drying–pyrolysis zone proposed by Ratnadhariya and Channiwala [5].

The products leaving the zone of drying and pyrolysis enter the second section, namely the oxidation zone. An accurately controlled amount of air is continuously supplied to the reactor in this section of the gasifier. In this zone combustible gases and solid fuel react with oxygen, contained in supplied air, to produce char, tar and a mixture of CO, CO₂, H₂, CH₄, N₂ gases and water vapour. The nitrogen fraction of supplied air is considered to be inert in the modeling process. The sub-model for the description of chemical

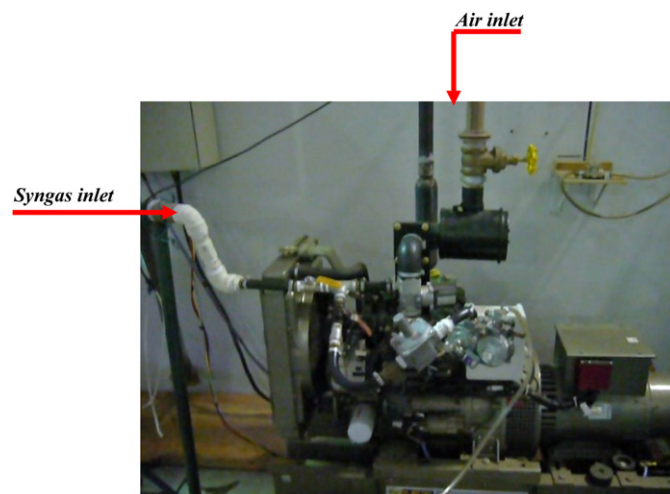


Fig. 3. A spark ignition internal combustion engine coupled to the gasifier.

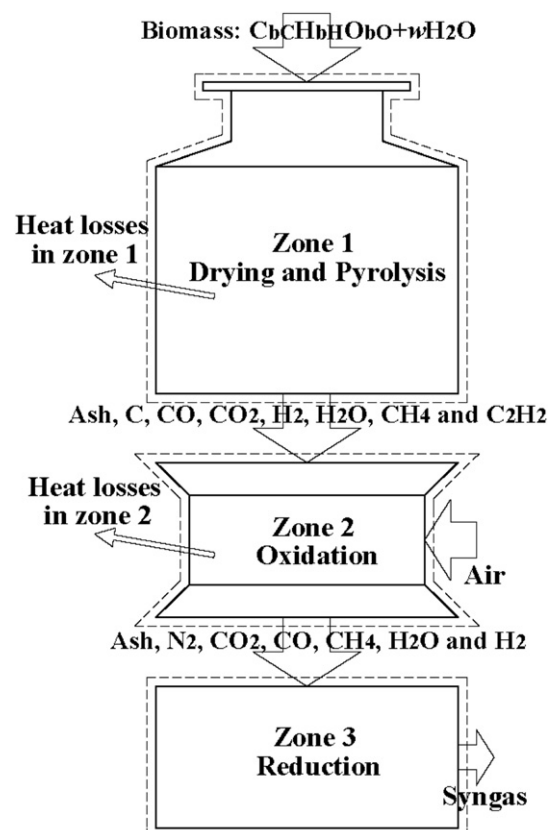


Fig. 4. A calculation scheme of the downdraft gasifier.

processes in the oxidation zone is based on the model proposed by Ratnadhariya and Channiwalwa [5] and Baxter [6].

The third (bottom) section of the reactor is the reduction zone also known as the gasification zone. In this section of the gasifier products formed in the oxidation zone react with each other according to the following four simultaneous reactions: the Boudouard, the water-gas (primary), the methanisation and the steam reforming. In the reduction zone nitrogen and tar are considered to be inert. The final products formed in this zone are CO, CO₂, H₂, CH₄, N₂ gases and water vapour with a relatively high concentration of combustible gases. The sub-model for the description of processes in the reduction zone of the biomass gasifier is based on proposals presented in studies by Giltrap et al. [1], Baxter [6], Giltrap [7] and Babu and Sheth [8].

4. Mathematical model of the gasifier

As described above, the mathematical model of the gasifier consists of three separate sub-models – one for each zone of the gasifier. In accordance with chemical analysis the wet biomass substance can be presented as the sum of the volatile and non-volatile components and water:

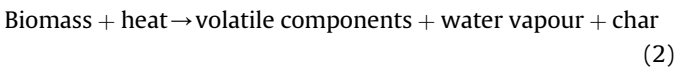


The main assumptions of the mathematical model are as follows:

- The amounts of nitrogen, sulfur and chlorine in the biomass material to be gasified can be neglected;
- The gasifier operates at the atmospheric pressure conditions;
- All gases in the gasifier can be treated as an ideal gas.

4.1. The drying–pyrolysis zone sub-model

Processes taking place in the drying–pyrolysis zone can be symbolically represented as:

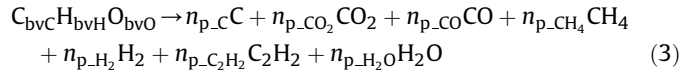


The main assumptions of the sub-model are as follows:

- The char is modelled as carbon graphite (non-volatile carbon) in accordance with Reed [9] and Channiwalwa [10];
- Only the volatile part of biomass $C_{bvC}H_{bvH}O_{bvO}$ undergoes the pyrolysis process. Non-volatile carbon and biomass moisture advance to the zone of oxidation, see Baxter [6];
- 4/5 of supplied oxygen reacts with hydrogen contained in biomass to form water (H₂O), see Mott and Spoone [11] and Channiwalwa and Parikh [12];
- 1/5 of supplied oxygen reacts with carbon contained in biomass to produce CO and CO₂, see Mott and Spoone [11] and Channiwalwa and Parikh [12];
- The ratio of moles of CO and CO₂ formed in the zone is equal to their molecular masses ratio, i.e. $n_{pCO}/n_{pCO_2} = 44/28$, see Storm et al. [13], Berends and Brem [14], Mastral et al. [15], Parikh et al. [16] and Van De Steene et al. [17];
- 50% of hydrogen available in fuel is released as H₂ during the decomposition process, see Storm et al. [13] and Parikh et al. [16];
- The remaining 50% of hydrogen available in fuel is released in the form of CH₄ and C₂H₂, see Storm et al. [13] and Parikh et al. [16];
- The ratio of moles of CH₄ and C₂H₂, formed in the gasifier, is inverse of their molecular masses ratio, i.e. $n_{pCH_4}/n_{pC_2H_2} =$

26/16, see Storm et al. [13]; Berends and Brem [14]; Mastral et al. [15]; Parikh et al. [16] and Van De Steene et al. [17].

The chemical reaction occurring in the zone can be presented as



The mass balance in the zone is

$$bvC = n_{pC} + n_{pCO_2} + n_{pCO} + n_{pCH_4} + 2n_{pC_2H_2} \quad (4)$$

$$bvH = 4n_{pCH_4} + 2n_{pH_2} + 2n_{pC_2H_2} + 2n_{pH_2O} \quad (5)$$

$$bvO = 2n_{pCO_2} + n_{pCO} + n_{pH_2O} \quad (6)$$

The energy balance in the zone is

$$\begin{aligned} \bar{h}_{fb} + w[\bar{\Delta h}_f]_{H_2O} = & n_{ptC}\bar{\Delta h}_{f_{ptC}} + n_{pCO_2}\bar{\Delta h}_{f_{pCO_2}} + n_{pCO}\bar{\Delta h}_{f_{pCO}} \\ & + n_{pCH_4}\bar{\Delta h}_{f_{pCH_4}} + n_{pH_2}\bar{\Delta h}_{f_{pH_2}} \\ & + n_{pC_2H_2}\bar{\Delta h}_{f_{pC_2H_2}} + n_{pH_2O}\bar{\Delta h}_{f_{pH_2O}} + Q_p \end{aligned} \quad (7)$$

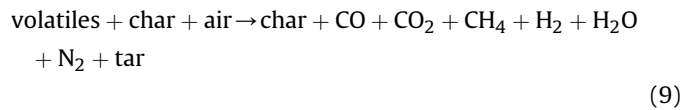
where

$$\bar{\Delta h}_f = \bar{h}_f + (\bar{h}_T - \bar{h}_{298}) \quad (8)$$

The heat losses in the drying–pyrolysis zone Q_p can be calculated using information on the temperature levels and thermo-physical properties of the wall and the insulation in the corresponding areas of the reactor.

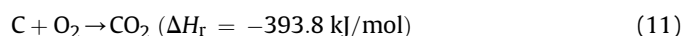
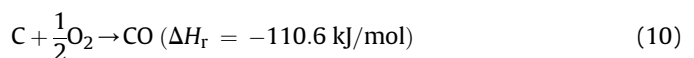
4.2. The oxidation zone sub-model

Processes taking place in this zone can be represented by the following reaction:



Assumptions of the sub-model for the oxidation zone are as follows:

- Acetylene formed during the pyrolysis process is fully oxidized;
- If a sufficient amount of oxygen is supplied then hydrogen formed in the pyrolysis process is fully oxidized and converted into water due its high burning rate, see Channiwalwa [10]; Thring [18]; Amundson and Arri [19]; Srinivas and Amundson [20]; Cho and Joseph [21] and Lewis and Von Elbe [22].
- The remaining oxygen is consumed in the process of char reduction, see Channiwalwa [10]; Thring [18]; Lewis and Von Elbe [22]; Gumz [23]; Evans and Emmons [24] and Bhagat [25].
- CO and CO₂ concentrations are considered to be inverse of the ratio of exothermicity of the corresponding reactions, i.e. less is the exothermicity of the reaction greater will be the rate of product formation, see Channiwalwa [10]; Thring [18]; Lewis and Von Elbe [22] and Gumz [23]. This is demonstrated for the following two main char oxidation reactions in the zone:



In accordance with the assumption made $n_{CO}/n_{CO_2} = 3.5606$.

- It is assumed that CO, CO₂ and H₂O produced during oxidation are added to the corresponding values of the same substances produced during pyrolysis;
- It is assumed that N₂ entering the oxidation zone is an inert gas and does not participate in chemical reactions;
- The products of reactions in the oxidation zone are char, CO, CO₂, CH₄, H₂, H₂O and N₂, see Giltrap [7] and Giltrap et al. [1].

The overall chemical reaction taking place in the oxidation zone can be presented as

$$\begin{aligned} n_{pt,C}C + n_{p,CO_2}CO_2 + n_{p,CO}CO + n_{p,CH_4}CH_4 + n_{p,H_2}H_2 \\ + n_{p,C_2H_2}C_2H_2 + n_{pt,H_2O}H_2O + a(O_2 + 3.76N_2) \rightarrow n_{ox,C}C \\ + n_{ox,CO_2}CO_2 + n_{ox,CO}CO + n_{ox,CH_4}CH_4 + n_{ox,H_2O}H_2O \\ + n_{ox,N_2}N_2 \end{aligned} \quad (12)$$

The corresponding mass balance equations in the oxidation zone are:

- For carbon

$$\begin{aligned} n_{pt,C} + n_{p,CO_2} + n_{p,CO} + n_{p,CH_4} + 2n_{p,C_2H_2} \\ = n_{ox,C} + n_{ox,CO_2} + n_{ox,CO} + n_{ox,CH_4} \end{aligned} \quad (13)$$

- For oxygen

$$2n_{p,CO_2} + n_{p,CO} + n_{pt,H_2O} + 2a = 2n_{ox,CO_2} + n_{ox,CO} + n_{ox,H_2O} \quad (14)$$

- For hydrogen

$$4n_{p,CH_4} + 2n_{p,H_2} + 2n_{p,C_2H_2} + 2n_{pt,H_2O} = 4n_{ox,CH_4} + 2n_{ox,H_2O} \quad (15)$$

- For nitrogen

$$2a(3.76) = 2n_{ox,N_2} \quad (16)$$

The energy balance equation for the oxidation zone can be written as

$$\begin{aligned} n_{pt,C}\bar{\Delta h}_{f_{pt,C}} + n_{p,CO_2}\bar{\Delta h}_{f_{p,CO_2}} + n_{p,CO}\bar{\Delta h}_{f_{p,CO}} + n_{p,CH_4}\bar{\Delta h}_{f_{p,CH_4}} \\ + n_{p,H_2}\bar{\Delta h}_{f_{p,H_2}} + n_{p,C_2H_2}\bar{\Delta h}_{f_{p,C_2H_2}} + n_{pt,H_2O}\bar{\Delta h}_{f_{pt,H_2O}} + a\bar{\Delta h}_{f_{O_2}} \\ + 3.76a\bar{\Delta h}_{f_{N_2}} \\ = n_{ox,C}\bar{\Delta h}_{f_{ox,C}} + n_{ox,CO_2}\bar{\Delta h}_{f_{ox,CO_2}} + n_{ox,CO}\bar{\Delta h}_{f_{ox,CO}} \\ + n_{ox,CH_4}\bar{\Delta h}_{f_{ox,CH_4}} + n_{ox,H_2}\bar{\Delta h}_{f_{ox,H_2}} + n_{ox,H_2O}\bar{\Delta h}_{f_{ox,H_2O}} \\ + n_{ox,N_2}\bar{\Delta h}_{f_{ox,N_2}} + h_{ox} \end{aligned} \quad (17)$$

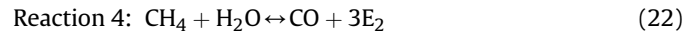
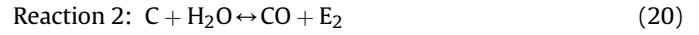
where

$$\bar{\Delta h}_f = \bar{h}_f + (\bar{h}_T - \bar{h}_{298}) \quad (18)$$

The heat losses Q_{ox} in the oxidation zone to ambient are calculated based on the temperature levels and the wall and insulation properties in this area.

4.3. The reduction zone sub-model

The sub-model for the reduction zone is based on the model that was originally presented by Giltrap [7] and Giltrap et al. [1]. In these articles authors propose that during the reduction process the following four simultaneous reactions take place:



The speed of each reaction is calculated based on principles of chemical kinetics:

$$r_1 = (CRF)A_1 e^{\left(\frac{-E_1}{RT}\right)} \left(P_{CO_2} - \frac{P_{CO}^2}{K_2}\right) \quad (23)$$

$$r_2 = (CRF)A_2 e^{\left(\frac{-E_2}{RT}\right)} \left(P_{H_2O} - \frac{P_{CO}P_{H_2}}{K_3}\right) \quad (24)$$

$$r_3 = (CRF)A_3 e^{\left(\frac{-E_3}{RT}\right)} \left(P_{H_2}^2 - \frac{P_{CH_4}}{K_4}\right) \quad (25)$$

$$r_4 = A_4 e^{\left(\frac{-E_4}{RT}\right)} \left(P_{CH_4}P_{H_2O} - \frac{P_{CO}P_{H_2}^3}{K_5}\right) \quad (26)$$

$$CRF = Ce^{bz} \quad (27)$$

where CRF is Char Reactivity Factor; $C = 1$; $b = 36.7$; z is the height of the reduction zone; A_i is the constant frequency factor for the i -reaction; E_i – the activation energy for the i -reaction; R is the universal gas constant and T is the temperature in the reduction zone. Table 2 shows the values of the frequency factors and activation energy for each reaction.

The char reactivity factor CRF was introduced by Babu and Sheth [8] to the model by Giltrap [7] and Giltrap et al. [1]. The sub-model for the reduction zone assumes a cylindrical form of the reduction zone with a uniform cross-section and neglects variations of gas properties in the radial direction. The mass (for six gas species) and energy balance equations, the ideal gas law and the equation of Ergun [26], which takes into account a pressure drop in the flow through a bed of particles, form the following complete set of nine differential equations with the corresponding number of unknowns parameters:

Table 2
Frequency factor and activation energy.

Reaction	A_i (1/s)	E_i (kJ/mol)
1	3.616×10	77.39
2	1.517×10^4	121.62
3	4.189×10^{-3}	19.21
4	7.301×10^{-2}	36.15

$$\frac{dn_x}{dz} = \frac{1}{v} \left(R_x - n_x \frac{dv}{dz} \right) \quad (28)$$

$$\frac{dT}{dz} = \frac{1}{v \sum_x n_x c_{xT}} \left(- \sum_i r_i \Delta H_i - v \frac{dP}{dz} - P \frac{dv}{dz} - \sum_x R_x c_{xT} T \right) \quad (29)$$

$$\frac{dv}{dz} = \frac{1}{\sum_x n_x c_{xv} + nR} \left(\frac{\sum_x n_x c_{xT} \sum_x R_x}{n} - \frac{\sum_i r_i \Delta H_i}{T} - \frac{dP}{dz} \left(\frac{v}{T} + \frac{v \sum_x n_x c_{xv}}{P} \right) - \sum_x R_x c_{xv} \right) \quad (30)$$

$$\frac{dP}{dz} = 1183 \left(\rho_{\text{gas}} \frac{v^2}{\rho_{\text{air}}} \right) + 388.19v - 79.896 \quad (31)$$

The Runge-Kutta method was used in Matlab software to solve the above system of the differential equations to obtain information on the distribution of the concentration of six gas species, the temperature, the velocity and the pressure along the height of the reduction zone.

5. Mathematical model of the engine

The fuel–air thermodynamics model was used to describe the operation of the syngas fuelled spark ignition engine. The detailed description of such a model can be found in the textbook by Ferguson [27] and the following are the main equations of this model which determine the calculation procedure for the engine.

During the operation of the spark ignition engine the mixture of fuel (syngas) and air is inducted into its cylinders through the inlet valve. For a control volume, which represents the cylinder with its content, the energy balance equation can be written as

$$m \frac{du}{d\theta} + u \frac{dm}{d\theta} = \frac{dQ}{d\theta} - P_{\text{en}} \frac{dV}{d\theta} - \dot{m}_l h_l \quad (32)$$

where m and u is the mass and internal energy of the mixture, respectively, in the cylinder of the engine; θ is the engine's crank angle; Q , P , V are the heat transfer into the system, the pressure in the cylinder, respectively; $\dot{m}_l$ and h_l are the mass flow rate and the enthalpy of the blow by gas, respectively; ω is the angular speed of the shaft.

The variation of the cylinder volume is defined as

$$V = V_0 \left[1 + \frac{r-1}{2} \left\{ 1 - \cos \theta + \frac{1}{\xi} \left[1 - \left(1 - \xi^2 \sin^2 \theta \right)^2 \right] \right\} \right] \quad (33)$$

where V_0 is the cylinder volume at the instance when the piston is at its top dead centre (TDC) position; r – is the compression ratio; $\xi = S/2l$ with S and l being the piston stroke and the connecting rod length, respectively.

It is assumed that internal energy of this system is made up of corresponding internal energies of burned and unburned mixtures as follows:

$$u = \chi u_b + (1 - \chi) u_u \quad (34)$$

where χ is the mass fraction of the cylinder content which was burned at the temperature T_b ; u_b and u_u is the energy of the burned gas and unburned gas at the corresponding temperatures T_b and T_u respectively.

Similarly, the specific volume of the system is

$$v = \frac{V}{m} = \chi v_b + (1 - \chi) v_u \quad (35)$$

The mass fraction χ is determined from the empirical burning law as follows:

$$\chi = \begin{cases} 0 & \theta < \theta_s \\ \frac{1}{2} \left\{ 1 - \cos \left[\frac{\pi(\theta - \theta_s)}{\theta_b} \right] \right\} & \theta_s < \theta < \theta_s + \theta_b \\ 1 & \theta > \theta_s + \theta_b \end{cases} \quad (36)$$

where θ_s and θ_b are the angular positions of the shaft corresponding to the start of the heat release and the burn angle, respectively.

The mass of the gas mixture in the cylinder is defined as

$$m = m_1 e^{\left[\frac{-C'(\theta - \theta_1)}{\omega} \right]} \quad (37)$$

where m_1 is the initial mass at $\theta = \theta_1$ (the start of the compression stroke) and is specified from knowledge of the volumetric efficiency and the residual fraction.

The amount of the gas lost as a result of leakage between walls of the cylinder and sealing rings is considerable in internal combustion engines and the change rate of the mass of the gas mixtures taking into account blow by can be expressed as

$$\frac{dm}{d\theta} = \frac{-\dot{m}_l}{\omega} = \frac{-C'm}{\omega} \quad (38)$$

where C' is the blow by constant dependent on the design of sealing rings and the cylinder.

The enthalpy of the blow by gas

$$h_l = (1 - \chi^2) h_u + \chi^2 h_b \quad (39)$$

and this expression takes into account that a larger proportion of the unburned gas will be leaking through sealing rings compared to the unburned gas mass fraction.

The magnitude of the heat introduced into the system will be expressed in terms of the heat loss:

$$\frac{dQ}{d\theta} = \frac{-\dot{Q}_l}{\omega} = \frac{-\dot{Q}_b - \dot{Q}_u}{\omega} \quad (40)$$

where

$$\dot{Q}_b = h A_{\text{htsb}} (T_b - T_{\text{wall}}) \quad (41)$$

$$\dot{Q}_u = h A_{\text{htsu}} (T_u - T_{\text{wall}}) \quad (42)$$

Here h is the average heat transfer coefficient; A_{hts} is the heat transfer surface and T_{wall} is the cylinder wall temperature.

The heat transfer surfaces are calculated as

$$A_{\text{htsb}} = \left(\frac{\pi b^2}{2} + \frac{4V}{b} \right) \chi^{1/2} \quad (43)$$

and

$$A_{\text{htsu}} = \left(\frac{\pi b^2}{2} + \frac{4V}{b} \right) (1 - \chi^{1/2}) \quad (44)$$

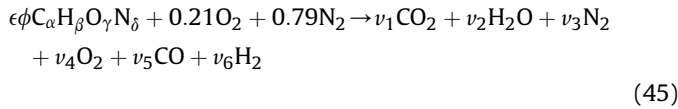
In calculations it is assumed that the pressures of the burned and unburned gases are equal.

The model employed also allows to determine the composition of the exhaust gases in the engine and the influence on the engine's performance of the fraction of the residual gases remaining in the cylinder at the beginning of the compression stroke.

Syngas is made of the mixture of combustible and incombustible gases and this was reflected in the description of fuel as having

a chemical composition $C_\alpha H_\beta O_\gamma N_\delta$, where coefficients α , β , γ and δ are defined using information on the syngas chemical composition.

The general combustion equation can be then written as

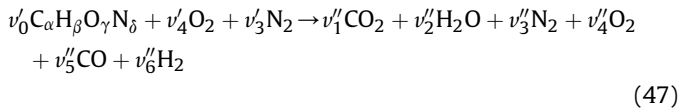


where $\phi = F/F_s$ is the fuel–air equivalence ratio with F and F_s being the actual and the stoichiometric fuel–air ratio.

The stoichiometric fuel–air ratio then can be determined as

$$F_s = \frac{\epsilon(12.01\alpha + 1.008\beta + 16.00\gamma + 14.01\delta)}{28.85} \quad (46)$$

To find the mole fraction of the residual gases at the beginning of the compression stroke the combustion equation is presented as



where ν'_i and ν''_i are reactant and product coefficients, respectively.

For the mixture of the residual gas and the premixed fuel–air

$$x_i = (1-f)x'_i + fx''_i \quad (48)$$

$$y_i = (1-y_r)y'_i + y_r y''_i \quad (49)$$

Here

$$x'_i = \frac{M'_i y'_i}{M'} \text{ with } M' = \sum_{i=1}^6 y'_i M'_i \quad (50)$$

$$x''_i = \frac{M''_i y''_i}{M''} \text{ with } M'' = \sum_{i=1}^6 y''_i M''_i \quad (51)$$

$$y'_i = \nu'_i / \sum_{i=1}^6 \nu'_i \quad (52)$$

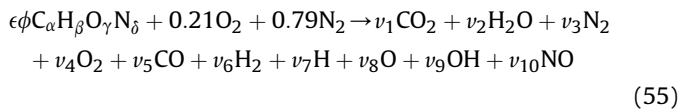
$$y''_i = \nu''_i / \sum_{i=1}^6 \nu''_i \quad (53)$$

The residual mole fraction is determined as

$$y_r = \left[1 + \frac{M'}{M''} \left(\frac{1}{f} - 1\right)\right]^{-1} \quad (54)$$

where f is the residual mass fraction and its numerical value should be defined before starting calculations.

The final composition of the products taking into account the main dissociation processes is defined as



where the values of coefficients ν_i are determined using atom-balancing and equations of equilibrium constants for corresponding dissociation equations for a given temperature.

The main equations of the model are that used to calculate the pressure in the cylinder, the temperature of its burned and unburned content and the work production:

$$\frac{dP_{en}}{d\theta} = \frac{A + B + C}{D + E} \quad (56)$$

$$\frac{dT_b}{d\theta} = \frac{-h\left(\frac{\pi b^2}{2} + \frac{4V}{b}\right)\chi^2(T_b - T_{wall})}{\omega m c_{pb}(1-\chi)} + \frac{\nu_b}{c_{pb}} \frac{\partial \ln \nu_b}{\partial \ln T_b} \left(\frac{A + B + C}{D + E}\right) + \frac{h_u - h_b}{c_{pb}} \left[\frac{d\chi}{d\theta} - \frac{(\chi - \chi^2)C'}{\omega}\right] \quad (57)$$

$$\frac{dT_u}{d\theta} = \frac{-h\left(\frac{\pi b^2}{2} + \frac{4V}{b}\right)\left(1 - \chi^2\right)(T_u - T_{wall})}{\omega m c_{pu}(1-\chi)} + \frac{\nu_u}{c_{pu}} \frac{\partial \ln \nu_u}{\partial \ln T_u} \left(\frac{A + B + C}{D + E}\right) \quad (58)$$

$$\frac{dw}{d\theta} = P_{en} \frac{dV}{d\theta} \quad (59)$$

The above parameters are influenced by the heat losses through the walls of cylinders and by the value of energy leaving the cylinder with the blow by gas:

$$\frac{dQ_l}{d\theta} = \frac{h}{\omega} \left(\frac{\pi b^2}{2} + \frac{4V}{b}\right) \left[\chi^2(T_b - T_{wall}) + \left(1 - \chi^2\right)(T_u - T_{wall})\right] \quad (60)$$

$$\frac{dH_l}{d\theta} = \frac{C'm}{\omega} \left[(1 - \chi^2)h_u + \chi^2 h_b\right] \quad (61)$$

In equations (56)–(61)

$$A = \frac{1}{m} \left(\frac{dV}{d\theta} + \frac{VC'}{\omega}\right) \quad (62)$$

$$B = h \frac{\left(\frac{\pi b^2}{2} + \frac{4V}{b}\right)}{\omega m} \left[\frac{\nu_b}{c_{pb}} \frac{\partial \ln \nu_b}{\partial \ln T_b} \chi^{1/2} \frac{T_b - T_{wall}}{T_b} + \frac{\nu_u}{c_{pu}} \frac{\partial \ln \nu_u}{\partial \ln T_u} (1 - \chi^{1/2}) \frac{T_u - T_{wall}}{T_{wall}}\right] \quad (63)$$

$$C = -(\nu_b - \nu_u) \frac{d\chi}{d\theta} - \nu_b \frac{\partial \ln \nu_b}{\partial \ln T_b} \frac{h_u - h_b}{c_{pb} T_b} \left[\frac{d\chi}{d\theta} - \frac{(\chi - \chi^2)C'}{\omega}\right] \quad (64)$$

$$D = \chi \left[\frac{\nu_b^2}{c_{pb} T_b} \left(\frac{\partial \ln \nu_b}{\partial \ln T_b}\right)^2 + \frac{\nu_b}{P_{en}} \frac{\partial \ln \nu_b}{\partial \ln P_{en}}\right] \quad (65)$$

$$E = (1 - \chi) \left[\frac{\nu_u^2}{c_{pu} T_u} \left(\frac{\partial \ln \nu_u}{\partial \ln T_u}\right)^2 + \frac{\nu_u}{P_{en}} \frac{\partial \ln \nu_u}{\partial \ln P_{en}}\right] \quad (66)$$

In the process of calculations the variations in the thermal properties of gases (ν , h , c_p), participating in the working process, with the temperature change are taken into account.

6. Validation of the gasifier and engine models

6.1. Calibration of the gasifier model

The predictions of the gas concentrations at the exit from the gasifier on the dry basis were produced using the proposed model

Table 3
Proximate and ultimate analysis of Rubber Wood, Jayah et al. (2003).

<i>Proximate analysis</i>	
Volatile material	80.1
Fixed carbon	19.2
Ash content	0.7
<i>Ultimate analysis (% dry basis)</i>	
C	50.6
H	6.5
N	0
Ash content (A)	0.7
O = 100 – (C + H + N + A)	42.2

and then these theoretical results were compared to experimental measurements performed by Jayah et al. [2]. Table 3 presents the results of the proximate and ultimate analysis, respectively, of biomass obtained experimentally by Jayah et al. [2]. Information in Table 3 was used as input data in calculations with the proposed model.

Table 4 shows the comparison of concentrations predicted by the proposed model against measured concentrations in the experiments by Jayah et al. [2] for different values of the moisture content and the air–fuel ratio. For all tests the standard deviation was calculated as $SD = (\sum_{i=1}^5 |y_{exp} - y_{mod}|_i) / 5$ where $i = 1 \dots 5$ represents each of the five species of gases considered (CO , CO_2 , CH_4 , H_2 , and N_2) and y_{exp} and y_{mod} represent the experimental and theoretical concentrations, respectively. It can be observed that for nine tests the average standard deviation is 1.12% which indicates a high accuracy of the model. As an example, Figs. 5 and 6 present results of comparison of experimental and theoretical data on the composition and the temperature of syngas, respectively, along the height of the reduction zone in the test number seven. It can be seen in Fig. 5 that the theoretical composition of syngas is very close to the experimental one. The temperature variation along the height of the reduction zone is calculated with a 50–150 K accuracy, see Fig. 6.

Further calibration of the model proposed in this work was carried out using experimental data obtained by Chee [28] and Senelwa [29] and theoretical modelling results by Giltrap [7] and

Table 4
Comparison of experimental (Jayah et al., 2003) and numerical (NEST Model) data on the composition of producer gas.

Test	Water content % w. b.	Air/fuel ratio	N ₂ (%)	CO ₂ (%)	CO (%)	CH ₄ (%)	H ₂ (%)	Standard deviation average %
1	18.5	2.03	51.9	9.9	19.6	1.4	17.2	1.280
2	16	2.2	53.9	11.1	18.9	1.0	15.1	1.972
			50.7	9.7	20.2	1.1	18.3	
3	14.7	2.37	54.5	10.8	19.2	0.9	14.5	1.372
			52.6	9.7	19.4	1.1	17.2	
4	16	1.96	55.0	10.6	19.6	0.9	14.0	0.815
			52.7	10.6	18.4	1.3	17.0	
5	15.2	2.12	53.9	11.1	18.7	1.1	15.2	0.637
			55.0	10.8	19.7	1.3	13.2	
6	14	2.29	54.4	10.9	19.1	1.0	14.7	1.775
			59.1	8.5	18.9	1.2	12.5	
7	14.7	1.86	54.9	10.7	19.4	0.9	14.2	0.339
			52.9	11.4	19.1	1.1	15.5	
8	13.8	2.04	53.7	11.3	18.4	1.2	15.4	1.402
			53.4	10.5	22.1	1.3	12.7	
			54.2	11.0	18.8	1.0	14.9	
			Experiment Jayah et al. (2003)					
NEST model								

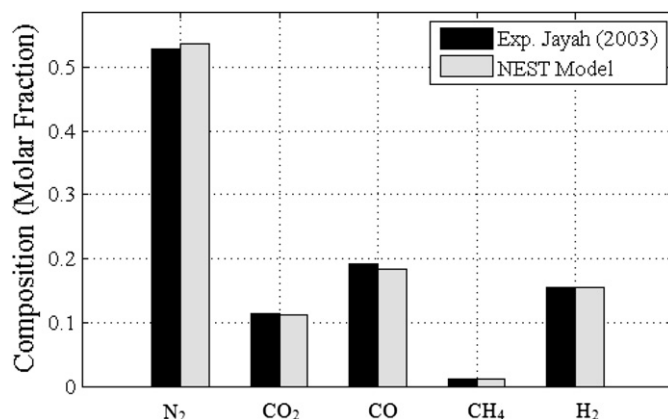


Fig. 5. Comparison of experimental and theoretical data on the composition of syngas.

Sharma [4]. Table 5 presents some of the parameters used in the experiments and in the theoretical modelling of the gasification process and Table 6 presents the results of the proximate and ultimate analyses of the Douglas fir tree bark used as biomass in the above investigations. Comparison of numerical results obtained using the proposed model with the theoretical results described by Giltrap [7] and Sharma [4] and with the experimental results described by Chee [28] and Senelwa [29] is illustrated in Fig. 7. It can be seen in this figure that the average deviation of results in the proposed model from experimental data on the composition of syngas is 3.2%. The proposed model provides a more accurate prediction of the CO and H_2 concentrations in syngas compared to other two theoretical models. Overall, the presented results indicate that the proposed model is capable to predict the composition of syngas with an acceptable accuracy.

Finally, the theoretical results obtained using the proposed model were compared to the experimental results produced in these investigations employing the gasifier shown in Figs. 1 and 2. The gasifier was tested when operating in the single-stage air-supply regime fuelled by wood blocks (eucalyptus). Table 7 shows results of the proximate and ultimate analyses of biomass which were used in tests. These biomass analysis results were deployed also as input data for modelling the gasifier and Table 8 presents comparison of theoretical and experimental information on the concentrations of CO , CH_4 and H_2 gases in syngas produced for values of the air factor ranging between 0.34 and 0.4. It can be seen that the model provides a satisfactory accuracy in prediction the

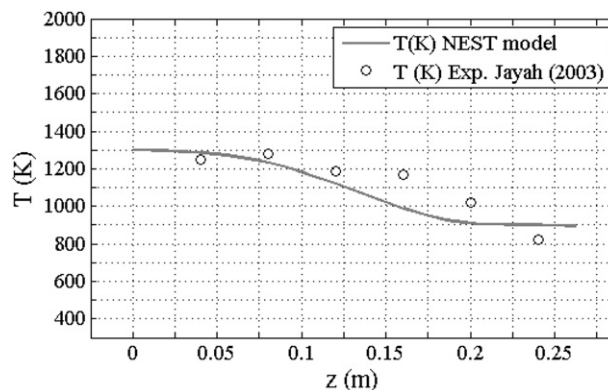


Fig. 6. Comparison of the experimental and theoretical temperature profiles in the reduction zone.

Table 5

Gasification parameters used during experiments and modeling.

Parameter	Chee (Experimental)	Senelwa (Experimental)	Present model (NEST)	Giltrap (Model)	Sharma (model)
The bed height, m	—	0.275	0.275	0.275	0.275 m
Biomass	Cotton stem	—	Douglas fir tree bark	Douglas fir tree bark	Douglas fir tree bark
Water content	5.4% w.b.	Dried in oven	5.4% w.b.	Dry	5.4% w.b.
Fuel/air equivalence ratio	1.67	—	1.67	—	(0.4)

concentrations of CO and H₂, but underestimates the production of methane.

Dissimilarity in experimental and theoretical results can be explained by a number of factors. Thus, due to the effect of vibrating mechanism the gasifier in real conditions operates in the unsteady regime. Furthermore, to improve the mathematical model's accuracy it is necessary to take into account all heat losses which take place during the operation of the gasifier and also the influence of the catalytic reformer reactor.

However, the overall accuracy of predictions by the proposed model is adequate for engineering purposes and it can be successfully used in the designing process.

6.2. Calibration of the engine's model

In reality syngas is a mixture of several gases such as hydrogen, carbon monoxide, methane and nitrogen. As highlighted in the description of the mathematical model of the engine syngas is assumed to be hydrocarbon fuel with a chemical composition being $C_\alpha H_\beta O_\gamma N_\delta$, where coefficients α , β , γ and δ are defined using information on the syngas chemical composition obtained during the gasifier modelling process. Data on the syngas composition is also used to calculate the calorific value of fuel. Due to this assumption made the heat release rate calculated during modelling the operation of the engine is not an accurate representation of the real syngas combustion process. Furthermore, an accurate quantitative prediction of pollutant emissions is an extremely challenging task even for most advanced mathematical models which take into account detailed kinetics of chemical reactions during the combustion processes in IC engines. Due to the assumptions described above the model is unable to accurately predict pollutants formation and more complex approaches should be deployed to resolve this problem. Therefore attention in this work is focused on presenting results on the integral performance characteristic of the engine such as its power output.

Table 6

Proximate and ultimate analysis of Douglas Fir tree bark.

<i>Proximate analysis</i>	
Parameter	% d. b.
Volatile material	73
Fixed carbon	25.8
Ash content	1.2
<i>Ultimate analysis</i>	
Parameter	%
C	56.2
H	5.9
N	0
Ash content (A)	1.2
$O = 100 - C + H + N + A$	36.7

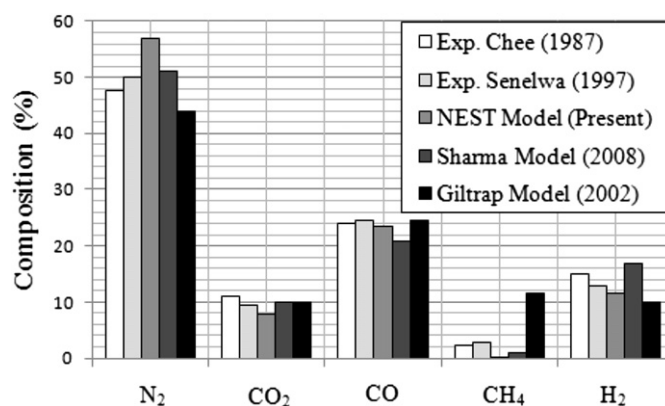
**Fig. 7.** Comparison of species concentrations obtained using various models and from experimental data.

Fig. 8 shows results obtained during the experiments with the modified Yanmar engine fuelled by syngas, which was produced by the single-stage air-supply downdraft gasifier, and results of modelling the performance of this engine. The experiments and modelling were performed for variable load–constant speed conditions, as it was described previously. In theoretical simulations of the engine's working process the composition of syngas was obtained using the gasifier's model. In experiments the electrical power output varied from about 1.5 to 5 kW_e at the engine's speed of 1800 rpm and it can be seen in Fig. 8 that at the higher loads the predicted values of the electrical power output are greater than experimental data. This can be explained by overestimation of the hydrogen concentration in syngas during modelling the gasifier operation. It was also found that the results of the engine modelling are very sensitive to the amount of air/fuel mixture in the cylinder at the beginning of the compression process and this value was assumed to be proportional to the positions of the regulating valves.

In general, the engine's model provides an acceptable accuracy in predicting the engine's performance and can be used jointly with the mathematical model of the gasifier for the analysis of the operation of the power system which includes a single-stage air-supply downdraft gasifier coupled to an internal combustion engine.

6.3. Mathematical modelling of the operation of the whole biomass power system

The mathematical models of the downdraft gasifier and of the engine were verified separately against experimental information

Table 7

Results of proximate and ultimate analysis of biomass (eucalyptus) used in tests.

<i>Eucalyptus</i>	
<i>Proximate analysis</i>	
Volatile matter	75.35
Ash	3.35
Fixed carbon	21.30
HHV	18.64 MJ/kg
Moisture	10.32
<i>Ultimate analysis</i>	
C	46.04
H	5.82
N	0
Ash	3.35
O	44.78

Table 8

Comparison of theoretical and experimental fractions of CO, CH₄ and H₂ gases in syngas.

Air factor	CO (%)	CH ₄ (%)	H ₂ (%)
0.34	16.98	1.88	16.25
	19.27	0.7	16.47
0.35	17.03	1.83	15.70
	19.39	0.68	16.27
0.36	16.66	1.98	14.84
	19.50	0.65	16.08
0.37	16.23	1.67	14.95
	19.61	0.63	15.89
0.38	15.66	1.76	14.54
	19.72	0.61	15.71
0.4	14.75	1.5	13.81
	19.93	0.58	15.36
Experimental results			
Modelling results			

and the comparison performed demonstrated a satisfactory accuracy of these mathematical models in the prediction of the gasifier and engine performance. In the following stage of investigations these two models were coupled together in such a way that output data from the gasifier's model was used as input information in the engine's model. The operation of the whole biomass power system for a range of values of different operational parameters such as the speed of the engine, the spark advancement, the air factor and the biomass moisture content was analyzed in order to quantify the influence of the above parameters on the overall performance of the system.

As expected, the mathematical model of the engine indicates that replacement of gasoline as fuel by syngas results in the considerable reduction in the power output and this is mainly due to the lower calorific value of syngas which reduces the heat release rate during the combustion process and results in lower values of the maximum pressure and temperature in the cylinder. The reduction in the power output is also affected by a decrease in the volumetric ratio of the engine.

Figs. 9–11 present some of results obtained. It can be seen in Fig. 9 that the indicated power of the engine fuelled by syngas rises with an increase in the engine speed and the power de-rating compared to the case, when gasoline is used as fuel, is about 50–60% for the engine's speed varying between 1500 and 2000 rpm. These calculations were conducted for the full throttle

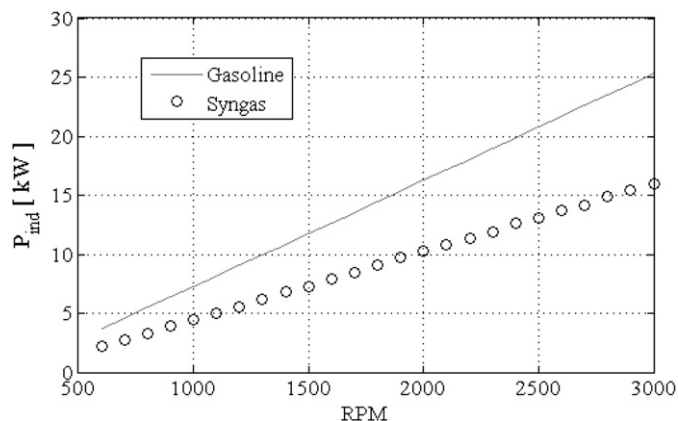


Fig. 9. Variation of the engine's indicated power as a function of the shaft speed.

operation when $\theta_s = -24^\circ$ before TDC and $\phi = 0.9434$. The increasing rate of the reduction of power for the case in which syngas is used as fuel is determined by the decrease in the volumetric ratio and by the reduction in the heat release rate during the combustion process of syngas.

Fig. 10 demonstrates that the highest maximum power for the engine running at the full throttle conditions at the 1800 rpm speed is achieved by setting the spark ignition to occur at the instance of the cycle corresponding to -25° – -30° before TDC.

Finally, Fig. 11 shows the influence of the gasifier air factor and biomass moisture on the indicated power of the engine running at the full throttle conditions at the speed of 1800 rpm. The air factor was varied between 0.25 and 0.4 and the moisture content was risen from 5 to 20%. Calculations show that the further rise in the biomass moisture content reduces the calorific value of syngas produced in the gasification process and, consequently, decreases the engine's power output. For a fixed value of the moisture content the indicated power sharply reduces with an increase in the air factor from 0.25 to 0.4. For the constant value of the air factor the indicated power of the engine increases with a rise in the moisture content from 5 to 20%. In both the cases the rise in the indicated power is a result of the improvement in the calorific value of syngas due to the greater concentrations of CH₄ and H₂, formed in the gasification process.

Judgment based Uncertainty Analysis [30] was used for evaluation of experimental data presented in Table 8 on the chemical composition of the syngas and in Fig. 8 on the electrical power

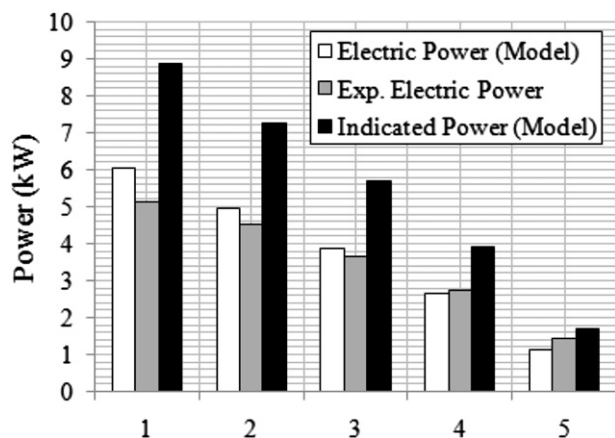


Fig. 8. Comparison of theoretical and experimental results on the engine power output. Electric Power (Model) – calculated value of the electrical power output; Ex. Electric Power – experimental value of the electrical power output; Indicated Power (Model) – engine's indicated power.

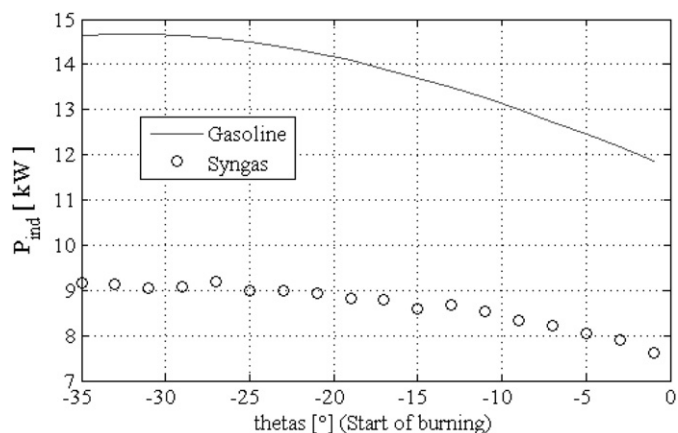


Fig. 10. Variation of the engine's indicated power as a function of the spark ignition timing.

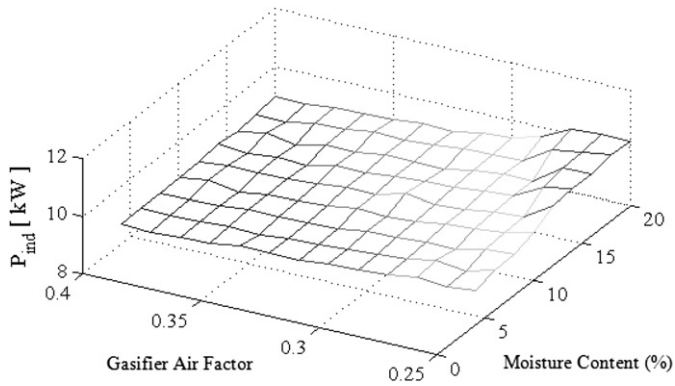


Fig. 11. Variation of the engine's indicated power as a function of the gasifier air factor and biomass moisture.

output of the engine. This analysis is based on manufacturer's specifications of resolution and uncertainty of instruments used for measuring the gas composition and of the electrical current parameters, on manufacturer's specifications of the electrical generator, the engine, the tachometer etc. Errors in measurements were combined using the root square sum method. Calculations performed indicate that measurements of the syngas composition are made with 10% uncertainty. The corresponding uncertainty of the measurement of the electrical power output in experiments is 16% (uncertainty bands are not shown in Fig. 8).

Information obtained as a result of the modelling of the whole system can be used for a refined adjustment of design parameters of the gasifier and the engine to achieve the higher overall efficiency of the biomass energy system.

7. Conclusions

A mathematical model to predict the steady state regime performance of a biomass power system including a fixed bed downdraft biomass gasifier with a single-stage air supply and coupled to a spark ignition internal combustion engine was developed and presented in this article.

The mathematical model consists of separate models for a downdraft biomass gasifier and an engine. In the mathematical model, the gasifier is split into three zones, namely the drying–pyrolysis, the oxidation and the reduction zones. There are three corresponding mathematical sub-models which describe relevant chemical reactions and energy and mass balances in each zone. The model's predictions for the syngas composition were validated by comparison to available published theoretical and experimental data and also to experimental data obtained in this work on the test rig for different air factor ratios. Simulation results obtained using the proposed model demonstrates are in a good agreement with experimental data published previously and produced in these investigations. Numerical results obtained in this project are also very close to theoretical results published in open literature. Realization of recommendations by Giltrap et al. [1] and including sub-models for the drying–pyrolysis and oxidation zones has improved the accuracy of predictions of the gas concentrations in the high temperature reduction zone without use of the pyrolysis factor, employed in the original model of Giltrap et al. [1].

The fuel–air thermodynamic model described by Ferguson [27] is at the core of the mathematical model used to analyze and predict the performance of the engine. This model takes into account the composition of syngas, the heat losses through the walls of the cylinders and losses due to blow by, the influence of the

residual gas presence in the engine's cylinder at the beginning of the compression stroke and, finally, the effect of dissociation processes. The theoretical results obtained using the engine's mathematical model are also in a satisfactory agreement with experimental data obtained on the engine as a part of investigations in this work.

After the mathematical models of the downdraft gasifier and of the engine were verified separately against experimental information, these were coupled to analyze the operation of the whole biomass power system for a wide range of operational parameters such as the speed of the engine, the spark advancement, the air factor and the biomass moisture content in order to quantify the influence of these parameters on the total performance of the system. The numerical results obtained from the coupled modelling of the gasifier and the engine as a whole biomass energy system can be used for the refined adjustment of design parameters of these two major components and to achieve the improved overall efficiency in the “biomass-to-energy” conversion process.

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Nomenclature

A, B, C, D, E constants

A_{hts} heat transfer surface in the engine, m^2

A_i frequency factor of the i -reaction in the gasifier

CRF char reactivity factor

E_i activation energy of the i -reaction in the gasifier, $J\ mol^{-1}$

F engine real fuel–air ratio

F_s engine stoichiometric fuel–air ratio

H enthalpy, J

K_i equilibrium constant for the i -reaction in the gasifier

M mass of reactants or products or mass of the i -species of reactants or products in the chemical equation of combustion of fuel in the engine, kg

P_{en} pressure in the cylinder, Pa

P total pressure in the gasifier, Pa

Q heat introduced into the engine cylinder, J

$\dot{Q}$ the engine heat introduction rate, W

R universal gas constant, $J\ mol^{-1}\ K^{-1}$

R_x net rate of creation of the x -species in the gasifier, $mol^{-1}\ m^{-3}\ s^{-1}$

S engine piston stroke, m

T temperature in the gasifier, K

T_u, T_b temperature of gases in engine, K

V the current cylinder volume, m^3

V_0 volume of the cylinder at the time instance when the piston is in its Top Dead Centre, m^3

W engine cyclic work, J

a moles of oxygen in the air entering the reactor, mol

b cylinder bore, m

c_p constant pressure heat capacity, $J/(kgK)$

c_x molar heat capacity of the x -specie, $J\ mol^{-1}\ K^{-1}$

f the residual mass fraction

h specific enthalpy, J/kg

h heat transfer coefficient, $W/(m^2K)$

l length of the connecting rod, m

n molar concentration of all gaseous species, $mol^{-1}\ m^{-3}$

$n_{ox,i}$	number of moles of the i -species produced in the oxidation zone, mol
$n_{p,i}$	number of moles of the i -species produced in the pyrolysis zone, mol
n_x	molar concentration of x -species, $\text{mol}^{-1} \text{m}^{-3}$
m	the current mass of the cylinder content, kg
m_1	the mass of the cylinder content at the start of compression stroke, kg
$\dot{m}$	mass flow rate, kg/s
r	compression ratio
r_i	reaction rate of the i -reaction in the gasifier, $\text{mol m}^{-3} \text{s}^{-1}$
x_i	the mass fraction of the i -product or reactant species in the chemical reaction in the engine
y_i	the volume fraction of the i -product or reactant species in the chemical reaction in the engine
u	specific internal energy, J/kg
v	gas velocity in the gasifier, m/s
w	moles of water in biomass per mole of carbon in biomass, mol/mol

Greek letters

$\Delta h_{\text{gr}_{ox-x}}$	enthalpy of the x -species at the temperature of oxidation, kJ mol^{-1}
$\Delta h_{\text{gr}_{p-x}}$	enthalpy of the x -species at the temperature of pyrolysis, kJ mol^{-1}
ϕ	the fuel–air equivalence ratio
θ	current angular position of the shaft, $^\circ$
θ_s	the angular position of the shaft corresponding to the start of the combustion process, $^\circ$
θ_b	the burn angle, $^\circ$
ρ_{air}	air density, kg m^{-3}
ρ_{gas}	gas density, kg m^{-3}
v	gas velocity, m s^{-1}
ω	engine shaft angular speed, rad/s
v	specific volume, m^3/kg
ν	coefficients or moles in the chemical equation of combustion, moles
χ	the mass fraction of the cylinder content which was burned

Superscripts

'	reactants in the chemical equation of combustion of fuel in the engine
"	products in the chemical equation of combustion of fuel in the engine

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b	burned
bC	moles of carbon per mole of total carbon in biomass
bH	moles of hydrogen per mole of total carbon in biomass
bnvC	moles of non-volatile carbon in biomass per mole of total carbon
bO	moles of oxygen per mole of total carbon in biomass
bvC	moles of volatile carbon per moles of biomass
bvH	moles of volatile hydrogen per mole of carbon in biomass
bvO	moles oxygen volatile per mole of carbon in biomass
en	engine
i	the i -reaction in the gasifier and the i -species of reactants or products in the chemical equation of combustion of fuel in the engine
res	residual gases
TDC	top dead centre
u	unburned
x	the x -species in the gasifier reactions
wall	wall

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